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EDITORIAL

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Special issue on the fluid mechanics of hypersonic flight

Higher and Faster

Dr. Sarah Popkin, AFOSR

Flow phenomena on maneuverable vehicles that fly at hypersonic speeds and altitudes that reach the Earth's upper stratosphere and lower mesosphere pose challenges that collectively form one of the present-day research frontiers of Fluid Mechanics. Research agencies around the world have realized the multiple benefits derived from transitioning a deeper understanding of hypersonic flow phenomena to actual flying platforms, and support for hypersonic research has increased substantially in the last decade. The result can be seen in Fig. 1, showing the distribution over years and originating countries of a total of 26,300 peer-reviewed research papers that have been published since the word *hypersonic* first appeared in the literature in the early 1940s and have this word in their title. Early peak activity subsided after the Moon landing, but soon picked up in the early 80s and again around the turn of the century, growing monotonically to the present day. As also shown in Fig. 1, a breakdown by country of origin reveals that two-thirds of the total number of hypersonic publications originate from the USA and China, giving rise to concerns raised by strategic think-tanks [57] and policy advisers [61] regarding potential misuse of hypersonic technology.

Hypersonic research has not always come to the limelight on account of potential strategic conflicts. The high plateau in number of papers published around the 1990s, shown in the left plate of Fig. 1, corresponds

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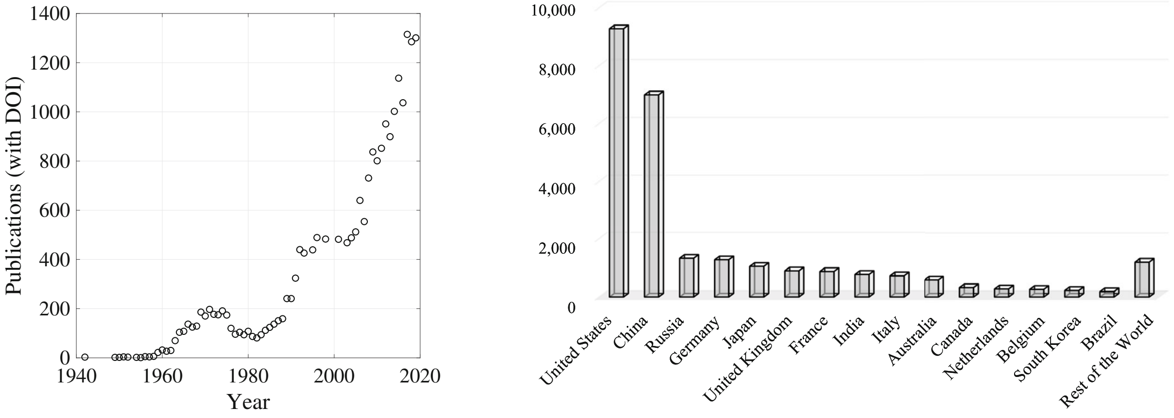

Fig. 1 Left: Peer-reviewed publications that contain the word *hypersonic* in their title. *Right:* Distribution by top publishing countries. (Source: www.scopus.com)

to intense activity that took place on the crest of the success of the early Space Shuttle flights, relating to the *new Orient Express* [47] of hypersonic travel. Large (and largely drawing board) projects involving substantial research into hypersonic flow physics, namely the *National Aerospace Plane* in the USA, *Buran* in the final years of the Soviet Union, *HOTOL* in the UK, *Hermes* in France and *Sänger* in Germany, alongside lower-scale efforts in India and Brazil, all testified to a time of optimism regarding hypersonic travel in a civilian transport context. Besides the obvious speed advantage when compared with current commercial air travel standards, impetus for research into hypersonic flight at higher altitudes is offered by the drastic reduction of the vehicle's noise fingerprint at ground level, which alleviates the sonic boom issues that affected supersonic flight (and the commercial success) of the Concorde. Snapshots of intense research activity of this period have been captured in monographs [4], the proceedings of long-running [50] or targeted conferences launched at that time [1], as well as in the three volumes that resulted from the Second and Third Joint US/Europe Short Course in Hypersonics, organized by the US Air Force Academy in Colorado Springs, the USA, in January 1989 and Aachen, Germany, in October 1990 [7–9]. The state of the art of that time in various facets of hypersonic technologies, such as numerical simulation of flow around full configurations [34], grid generation [18,58], modeling of reacting- [42] and non-equilibrium [28] flows, boundary-layer laminar–turbulent transition [59] and engineering computation of turbulence at hypersonic speeds [38], is documented in these three volumes and largely forms the basis of engineering prediction tools still in use today.

However, any notion that hypersonic flight can rely on mature technologies arising from understanding of the relevant Aerothermodynamics/Fluid Mechanics phenomena is simply erroneous. Altitudes of current interest for maneuverable hypersonic flight, typically 40-70km, correspond to the currently least understood layers of the Earth's atmosphere, collectively nicknamed the "*ignorosphere*." Two reviews of Bertin and Cummings [5,6], the second written in the aftermath of the STS-107 disaster, highlighted critical hypersonic aerothermodynamic phenomena hampering routine engineering design of flight vehicles, on account of poorly understood flow physics; laminar–turbulent transition in hypersonic boundary layers, an ubiquitous phenomenon at different regions of the vehicle throughout its trajectory, is a predominant example of research area dependent on a number of both *known unknowns* and *unknown unknowns* [6].

Flow instability and laminar–turbulent transition underpins many of the contributions to this Special Issue and clearly highlights the need for continued hypersonic research. Put simply, all other parameters being kept constant, as the density of air decreases exponentially with altitude, the Reynolds number will also decrease and turbulent flow in the boundary layer skin around the vehicle at sea level, or that in its wake, will become laminar when the flight altitude is sufficiently high, such that in the lower mesosphere flow is expected to be *predominantly laminar* [6]. The notoriously multi-parametric nature of the transition problem

[37] is exacerbated by new unknowns related to shock waves, their interaction with the boundary layer and the response of the constituent gases of the Earth's atmosphere to the various temperature regimes relevant to hypersonic flight at different altitudes. Knowledge obtained under idealized conditions of smooth walls composed of materials that maintain their constitution at high temperatures is at best the first approximation to real surfaces made of rough ablative materials used to shield the vehicle structure from the extreme temperatures [66]. The state of confusion surrounding hypersonic laminar–turbulent transition around the turn of the century is exemplified in the following passage from Bertin [4]

> In 1969, Morkovin [39] stated that *Time and again some of the implicit parameters are changed and the prediction bands may be rendered inapplicable to the new problem*.
> In 1975, Reshotko [48] stated that *These efforts, however, have yielded neither a transition theory nor any even moderately reliable means of predicting transition Reynolds number*.
> In 1992, Stetson [59] stated that *There is no transition theory. All transition prediction methods are empirical*.

These overly pessimistic views have now somewhat receded, no doubt on account of substantial efforts having been invested in building and successfully operating quiet wind tunnels [55] and major theoretical and computational advances that have taken place in the last thirty years. Regarding addressing high-enthalpy conditions that lead to high gas temperatures past shocks and, in turn, potentially activate a suite of real gas effects [6], simulations can rely on mature numerical approaches based on both the Navier–Stokes equations [44] and kinetic theory methods [30,32]. In the former context, a suite of schemes has been demonstrated to accurate capture receptivity, instability and transition in hypersonic boundary layers [67]. In the context of kinetic theories, the Direct Simulation Monte Carlo (DSMC) method [10,11] is particularly well suited to fully resolve unsteady shocks and shock interactions (as opposed to the need to model the internal shock structure in Navier–Stokes-based simulations), as well as naturally incorporate surface chemistry into the simulation, and is now routinely employed to further understanding of hypersonic flows. Efforts to characterize and model non-equilibrium flows with internal energy excitation, chemical reactions, ionization and gas–surface interactions continue [12]. Linear stability theory itself has experienced step-change improvements in the last two decades. The interpretation of classic linear theory results in high-speed boundary layers has been enriched [24], and the scope of the theory has been broadened to include flows with multiple inhomogeneous spatial directions [62], as naturally arising in hypersonic regime on account of shock interactions. Also, the distinction between asymptotic and transient growth of linear perturbations has been understood [31,49,54,65] and is applied to analyze long-standing hypersonic transition problems [41] as well as to address instability on three-dimensional geometries relevant to hypersonic flight [46].

Summary of articles in this special issue

Against this background, *the dream of the graceful spaceplane is still live* [43] and hypersonic flight once again returns within the field of vision of the wider public (and politicians). Intense efforts exist worldwide, a very small sample of which has been collected in the present Special Issue on *The Fluid Mechanics of Hypersonic Flight*; a tandem publication with the same title appears as a Topical Collection in our sister journal *Experiments in Fluids*. Contributed papers have been solicited from the wider community of practitioners as well as from the Principal Investigators attending the 2020 AFOSR/ONR/HVSI Hypersonic Aerodynamics Portfolios Review. Submissions to the Special Issue underwent the standard reviewing process, and fifteen accepted papers are presented in the first two issues of the present volume.

Contributions to the Special Issue include fundamental work and applications of existing tools to understand phenomena occurring in hypersonic flow in both canonical and application-related configurations. Four publications discuss state-of-the-art kinetic theory methods which resolve shock layers and permit unravelling the internal shock structure. A novel Boltzmann solution method, denominated quasi-particle simulation (QuiPS), is presented by Poondla, Goldstein, Varghese, Clarke and Moore [45], who implemented chemistry for five-species air and demonstrated efficient recovery of results at re-entry conditions. Compared to classic

Direct Simulation Monte Carlo (DSMC) methods, QuiPS is reported to reduce the noise inherent to particle simulations, although results have only been discussed at near chemical equilibrium rarefied flow conditions. Torres and Schwartzentruber [63] employ direct molecular simulations (DMSs) of rovibrational excitation and dissociation of oxygen across normal shock waves, relying exclusively on ab initio potential energy surfaces to describe the full collision dynamics in a mixture of molecular and atomic oxygen. They demonstrate that DMS results offer a first-principles methodology to delimit the region where continuum breakdown occurs across a normal shock. Sawant, Levin and Theofilis [52] further expand upon their recent discovery [53] of low-frequency molecular fluctuations arising in the non-equilibrium zone of straight shocks away from solid boundaries, a phenomenon that arises on account of bimodality of the probability distribution function (PDF) employed in DSMC, which is absent in the (typically Maxwellian) PDF assumption underlying the Navier–Stokes equations. In the present contribution, the low frequencies in question have been modeled using analytically derived PDFs of particle energies in local equilibrium and results were tabulated in the range of $3 \leq M_\infty \leq 10$; the latter can be used to incorporate physics-based representation of the internal shock structure in receptivity and linear stability analysis work that includes shocks. Klothakis, Quintanilha, Sawant, Protopapadakis, Theofilis and Levin [33] solve the steady laminar flow over a semi-infinite flat plate using DSMC and find the results to be in good agreement with those delivered by boundary layer profiles obtained under appropriate slip velocity and temperature jump boundary conditions. Subsequently, they compare the linear stability characteristics of the DSMC base flows with those delivered by classic Navier–Stokes-based profiles. They find the respective full spectra of three different monatomic and diatomic gases to be in very good agreement with each other over a wide Mach number range, DSMC-obtained flows being slightly more stable than their Navier–Stokes counterparts. Large-scale unsteadiness introduced by a wall-jet and simulated by DSMC led to synchronized oscillations inside the boundary layer and in the shock layer, the characteristics of which have been predicted by linear stability theory.

In the framework of Navier–Stokes-based linear stability analyses, both fundamental work and flows on components relevant to hypersonic flight have received attention. Along the former theme, Fedorov and Tumin [25] revisit the classical laminar–turbulent transition prediction tool proposed by Mack [37], which relies on the broadband nature of the spectrum of environmental disturbances, and put the criterion on firm theoretical basis by evaluating the (time and space) double integral by a novel asymptotic method. Results obtained by the proposed method compare favorably with those of direct numerical simulation (DNS) and highlight the need for quantitative error bounds arising from receptivity analysis to be introduced into engineering tools, if confidence in the results delivered by such tools is to increase. Cook and Nichols [16] address the problem of linear stability in the vicinity of a shock and propose a boundary condition based on the Rankine–Hugoniot conditions, which permits including small-amplitude shock motion into modal and non-modal instability analyses. Although no comparisons between the well-known Rankine–Hugoniot-based boundary conditions for local linear stability analysis [13,23] and the novel conditions have been presented, the proposed closure has been implemented into a global non-modal linear analysis framework and applied to study instabilities of $M_\infty = 5.8$ flow in the vicinity of a blunted-nose cone. Significant amplification of low-frequency perturbations in the cone frustum as well as amplification of entropy perturbations at higher frequencies has been discovered, further highlighting the need for attention to shock boundary conditions to be paid in the context of hypersonic stability calculations. Dettenrieder and Bodony [19] address flow–structure interaction and discuss the effect of mechanical wall compliance on compressible laminar boundary layer stability. They derive and solve a coupled system of linear stability equations in which two non-dimensional interaction parameters have been introduced to describe flow instability and wall compliance in a coupled manner. They show that the well-known compressible boundary layer theory results [37] are modified in a non-monotonic manner by wall compliance and (substantially) more research is required in the context of compliant walls before the established linear stability theory can be applied with confidence to vehicle design.

A number of contributions addressed instabilities pertinent to hypersonic flowfields arising on (sections of) vehicles at cruise or maneuvering phases of flight. Choudhari, Li, Paredes and Duan [14] employ the appropriate for inhomogeneous laminar flows PSE-3D/“plane-marching PSE” [17] to address high-frequency instabilities of azimuthally compact crossflow vortices arising on a circular-base 7° half-angle cone that is yawed against

$M_\infty = 6$ oncoming flow. The nonlinear crossflow vortex evolution and the linear amplification characteristics of high-frequency instabilities evolving in the presence of these azimuthally inhomogeneous vortices have been described, and it is found, perhaps unsurprisingly, that results of PSE-3D match those of DNS much closer than those of the corresponding local analysis which ignores azimuthal base flow inhomogeneity. Li, Choudhari and Paredes [35] examine Görtler vortices in $M_\infty = 6$ flow over a concave axisymmetric geometry using DNS and secondary stability analysis. They find that at low amplitudes the amplification of linear perturbations captured in DNS corresponds to that predicted by linear non-modal (global) stability theory and that mushroom-like structures known from incompressible flow analyses are also present at hypersonic conditions as a result of large amplitude of the Görtler vortices. Secondary PSE-3D analysis of these structures reveals the existence of supersonic secondary instabilities of stationary Görtler modes generating acoustic radiation to the flow just outside of the boundary layer. In related work, also addressing linear stability of Görtler vortices over a wide range of free-stream Mach numbers, $2 \leq M_\infty \leq 6$ at the asymptotically high Reynolds number regime, Es-Sahli, Sescu, Afsar and Hattori [22] employ numerically efficient computations of the nonlinear compressible counterpart of the boundary region equations (BRE) [21,27,51]. Results of the method have been validated against DNS, and it is claimed that, from a numerical point of view, the BRE are more efficient than the PSE (or DNS). Parametric studies are performed to elucidate the effect of spanwise spacing and Mach number on integral flow quantities; however, comparisons with results obtained by other analyses of the same problem have not been presented. On the same theme of flow instabilities in three-dimensional boundary layers on concave surfaces, Mullen and Reed [40] perform high-resolution DNS of flow around the BOLT geometry at nominal conditions and nonzero pitch and yaw angles, followed by systematic linear stability analyses of interesting zones in the flow. Concerns have been raised by these authors regarding the level of numerical convergence of the centerline structures, both in the work presented and in earlier DNS work in the literature, while flow at locations away from the centerline has been shown to be fully converged. Systematic stability analyses using the appropriate parabolized stability equations (PSE) tools are carried out on base states in the latter regions, where experiments documented transition, and second mode, crossflow instability and related N-factors are fully documented. Off-nominal flight conditions have also been analyzed, the relative significance of different instability modes has been characterized within the PSE framework, and flowfield regions for future global stability analyses of three-dimensional flows have been identified.

Finally, contributions to this volume employed state-of-the-art numerical simulations of the compressible Navier–Stokes equations to characterize hypersonic flows in both canonical and applied configurations. Lugrin, Beneddine, Garnier and Bur [36] perform large-scale simulations and linear stability analyses of $M_\infty = 6$ flow on a hollow cylinder/flare configuration for which experimental data are available. Wall-resolved large Eddy simulations were used to resolve transitional flow features, followed by data-driven and operator-driven [60] analyses of the results, respectively, employing Spectral POD [56,64] and mean flow stability analysis [3]. It is found that the dynamics of the flow is dominated by a denominated *bubble* mode, the frequency of which is comparable with that of averaging time of the flow and corresponds to the well-known low-frequency oscillations reported in experiments and analyses of turbulent separated flows [15]. Solution of the adjoint problem has also been used to compute the wavemaker and propose the physical mechanism of the observed instability scenario. Three-dimensional turbulent separation effects are at the core of the work of Adler and Gaitonde [2], who address the issue of separation arising from shock/boundary layer interactions in three-dimensional configurations of increasing geometric complexity. Using a very large database of experimental and simulation results, these authors catalog unsteady phenomena on the basis of frequency bands and describe qualitative differences between two-dimensional, axisymmetric, open three-dimensional separation in the absence of sidewalls, as well as the effect of the latter on the proposed characterization. Di Renzo, Oberoi, Larsson and Pirozzoli [20] use DNS to address the fundamental problem of shock wave/turbulent boundary layer interaction in the presence of three-dimensionality induced by crossflow. In line with predictions of earlier high-fidelity DNS work [29], these authors find an augmentation of the (mean) size of the separation bubble, associated by changes in the mean flow direction. Strong non-equilibrium of turbulence is documented, which can be used in future efforts aiming at increasing the reliability of compressible turbulence models. Interestingly, one such modeling approach, the wall-modeled large Eddy simulation (WMLES) employed by Fu, Bose and Moin [26] in their predictions of aerothermal characteristics of Mach 8.3 flow over a double-finned geometry, makes use of the assumption of turbulence in equilibrium. However, these authors stress that a semi-local eddy viscosity approach should also be used, instead of van Driest scaling, if surface pressure loading and heat fluxes are to be accurately predicted; they go on to demonstrate very good agreement of experimental results with mean flow quantities obtained in their computations.

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